emc europe 2006 barcelona

3D FEM MODEL FOR LOCALISED *SAR* ESTIMATE IN HUMAN EXPOSURE TO MICROWAVES

Mihaela Morega, Al. M. Morega and Alina Machedon
Department of Electrical Engineering, POLITEHNICA University of Bucharest
313 Splaiul Independentei, zip code 06004, Bucharest, Romania
E-mail: mihaela@iem.pub.ro

Abstract: Exposure of living bodies to very high frequency non-ionizing electromagnetic field (EMF) (i.e. microwave (MW) domain, (10^8 – 10^{11}) Hz) is associated to the use of mobile communications, radar detection, dielectric heaters and to several medical procedures. Phantoms filled with artificial materials described by dielectric properties similar to those of anatomical tissues are used in experimental procedures for electronic equipment certification; numerical modeling is also a powerful tool for EMF distribution and dosimetric parameters evaluation, while an optimum between computational costs and relevance of results is desirable.

We report here a numerical study of the electromagnetic field induced in several biological 3D FEM models by a conventional microwave applicator. The sensitivity of dosimetric parameters relative to the properties of the model and the compliance with exposure guidelines are evaluated. The influence of dielectric properties dispersion on dosimetric quantities is examined. Useful conclusions were drawn for the design and validation of experimental settings and numerical models. The general characteristics of the MW source and the exposed medium are associated to mobile telephony conditions, but the methods could be also extended to other applications.

I. INTRODUCTION

Microwave dosimetry consists of three categories of problems [1]:
(1) specification of the exposure conditions: EMF source and characteristics of the target body (shape and inner structure with physical properties),
(2) evaluation of the so-called internal fields, namely the electric and magnetic fields distributions inside the body exposed to the incident fields,
(3) estimation of the biological effects.

An antenna, usually placed near the surface of the skin, is the EMF source. Excited with electromagnetic radiation in the MW domain, biological tissues are materials that behave, at a macroscopic scale, as lossy dielectrics; the depth of penetration is limited in those circumstances to 0.02 – 0.03 m. Consequently, the exposure of living bodies to very high frequency non-ionising EMF may lead to significant absorption of energy mainly localized at the surface of the exposed body. The energy absorption is related to thermal effects and is usually quantified by the Specific energy Absorption Rate ($SAR = \sigma E_{max}^2 /(2\rho)$ where E_{max} is the maximum value of the time harmonic strength of the electric field **E**, σ is the electric conductivity and ρ is the mass density of the exposed tissue). Thermal biological effects are intensively studied and documented; currently, limiting exposure restrictions are exclusively based on thermal effects. However, athermal physiologic phenomena are suspected to occur and make the object of important but yet inconclusive research in this field.

Experimental evaluation and computation of EMF distribution inside the exposed body are the two ways that allow the investigation of dosimetric parameters. Macroscopic analysis generates data on the distribution of the EMF inside the exposed body and opens the path for microscopic dosimetry. Inner electric field is measured either in experimental animals or in models (phantoms) which consist of materials that have electric and magnetic properties similar to that of animal tissue; the measurements follow standard protocols in order to minimize the uncertainties. The numerical modeling allows detailed description of the exposure conditions and sophisticated processing of data, but is highly dependent on expensive computational resources. The usefulness of numerical modeling as well as measurements inside the body is beyond doubt for the assessment of biological effects necessary for setting the safety exposure guidelines; the two evaluation tools could complement each other in the design of harmless MW devices and in the development of certification protocols.

The objective of our research is to present and evaluate simplified numerical models for dosimetric studies in the MW domain of the EMF. This work is focused on the construction of a 3D model adequate for the study of EMF penetration and dosimetric estimates in the head of a cellular phone user, but the followed path and the tools are adequate for any other application. The 3D human head model presented here has a realistic shape, obtained through geometrical reconstruction from 2D tomographic slices. Its inner structure is represented by a homogeneous tissue with equivalent physical properties. We show in this paper the construction of the 3D geometry, the computation of the equivalent dielectric properties and *SAR* calculation according to effective exposure guidelines.

II. PHYSICAL PROPERTIES OF THE MODEL AND GENERAL CONSIDERATIONS

The work presented here examines the electromagnetic field penetration in human tissue considering several conditions and particularities related to wireless communications in the microwave frequency range [2-4]:

(1) An antenna is the electromagnetic radiation source in our near field exposure study. In this region, approximately one wavelength in extent, the electric field strength can be relatively high and pose a hazard to the human body. The dipole configuration is the most common and conventional type for near field human exposure related to wireless personal communication systems in the GSM frequency range (0.5 to 3 GHz) and the time-harmonic waveform is considered. In numerical and experimental models, the length of the antenna is usually adjusted at the half wavelength, both because of modeling reasons (like symmetry conditions) and to maximize the efficiency of the emission.

(2) The exposed body model is inspired by the human head anatomy. A 3D reconstruction from 2D tomographic slices that conserves the general external shape of the head was performed. The model is compared with another with ellipsoidal shape. Both models have a homogeneous inner structure described with equivalent physical properties.

(3) Our purpose is to determine some quantitative and qualitative information on dosimetric parameters inside the body exposed to electromagnetic radiation and to relate them to prescriptions stated in human exposure guidelines and standards [5-8]. We are interested here by the high-frequency electromagnetic field, the microwave range with applications in wireless communications technologies, 0.5 – 3 GHz. The basic restriction for localized exposure (head and trunk) in this frequency range is the specific energy absorption rate (*SAR*) which is set in terms of maximum mass-normalized quantity, as follows:

- 2 W/kg for "any 10g of contiguous tissue" in the ICNIRP guidelines [5] and the EC recommendation [8], while "any 10g of contiguous tissue in the shape of a cube" in the Australian standard [7];
- 1.6 W/kg for "1g of tissue in the shape of a cube" in the ANSI/IEEE standard [6].

Basic references [5], [6] and [8] are issued in the same period of time, 1998-1999, are based on the research and documentation literature available at the time and are still in force. At the first glance the specifications do not seem to be contradictory; however, we found some differences in their practical use, that we attempt to emphasize on a case study presented further.

III. 3D HEAD MODEL CONSTRUCTION

The 3D reconstruction of the human head [2] is accomplished with the aid of the Matlab – Femlab software suite [9], after the preprocessing of the data with 3D Slicer [10]. Femlab is an interactive environment for modeling and solving FEM based problems, while 3D Slicer is an image processor, capable of volumes reconstruction from 2D slices. The primary data used are CT images scanned from an adult person, as a series of cross-sectional images made along an axis; the images are segmented (the regions of interest are identified on the image – in our case the whole head) using a combination of manual and semiautomatic segmentation. From these images the head is reconstructed in 3D Slicer as fig. 1 shows.

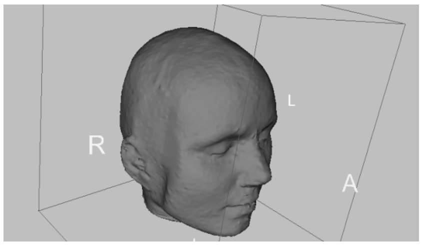


Fig. 1. The head reconstructed in 3D Slicer

The images segmented in 3D Slicer were used as the basis of the reconstruction with the Matlab-Femlab suite and the final object is rendered in Femlab. A conventional half wavelength dipole antenna is located near the right ear; the outer domain, the space around the head, is limited with a sphere (fig. 2).

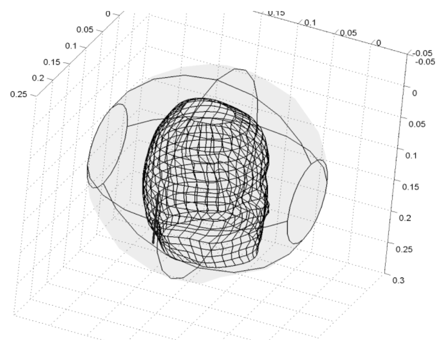
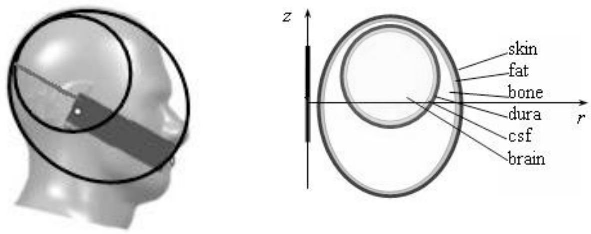


Fig. 2. Human head geometry in Femlab

Computational resources impose restrictions for the representation of the head anatomical structure. An inner structure described by thin tissue layeres, like the one presented in [3], requires large computer memory for the discretization mesh, which proves to be an excessive demand for our available resources. The solution to this problem is a compromise. We computed equivalent dielectric properties by energetic equivalence between the EMF distributions in a six tissues layered structure and in a homogeneous one. The equivalence is performed on 2D models reduced from 3D based on axial symmetry hypothesys. Fig. 3 sugests the assumptions made here: (a) the geometrical configuration could be approximated with elipsoidal and spherical layers; (b) the axial symmetry which is adequate for the antenna, proves to be also suitable for a practical, even unrealistic, anatomical structure.



a. General configuration b. 2D model (6 tissue layers)

Fig. 3. Computational 2D domain based on a multi-layered structure

The numerical computation used for the 2D FEM model is based on the Femlab software [9], the *Electromagnetics Module*, in the *axisymmetric transversal magnetic (TM) waves* application mode, *time-harmonic* submode. The wave equations are applied for lossy media, characterized by the complex electric permittivity $\underline{\varepsilon}$

$$\nabla\times\left(\frac{1}{\mu_0}\nabla\times\underline{\mathbf{E}}\right)-\omega^2\underline{\varepsilon}\,\underline{\mathbf{E}}=0\,, \qquad (1)$$

$$\nabla\times\left(\frac{1}{\underline{\varepsilon}}\nabla\times\underline{\mathbf{H}}\right)-\omega^2\mu_0\underline{\mathbf{H}}=0\,, \qquad (2)$$

where the unknown field variables, in the cylindrical coordinate system and in complex form are:

$$\underline{\mathbf{H}}(r,z,t)=\underline{H}_{\varphi}(r,z)\mathbf{e}_{\varphi}e^{j\omega t} \qquad (3)$$

$$\underline{\mathbf{E}}(r,z,t)=\left(\underline{E}_r(r,z)\mathbf{e}_r+\underline{E}_z(r,z)\mathbf{e}_z\right)e^{j\omega t} \qquad (4)$$

The computational domain is limited with *low-reflecting* boundary conditions and the boundary on the (*Oz*) axis satisfies *axial symmetry* conditions. The EMF source is introduced through a nonhomogeneous *magnetic field* boundary condition, simulating the center fed dipole antenna. The dielectric properties and dimensions for the six tissue layeres were taken from literature [3, 11], in the considered frequency range (0.5 ... 3) GHz.

A linear stationary solver based on Gaussian elimination was used. The FEM mesh is composed of triangular elements, and for its density assessment were performed two accuracy tests: the constant radiated power and the conventional energetic balance in the domain.

Energy based equivalence methods were applied to compute dielectric properties of the reduced homogeneous model (σ_{equiv} respectively ε_{equiv}). One considers that the total absorbed power and the total electric energy have the same values in the heterogeneous (composed by *i* different sub-domains) and equivalent homogeneous models:

$$\int_i \sigma_i (E_i)^2\,\mathrm{dv} = \sigma_{equiv}\int_i (E_i)^2\,\mathrm{dv}\,, \qquad (5)$$

$$\int_i \frac{1}{2}\varepsilon_i (E_i)^2\,\mathrm{dv} = \frac{1}{2}\varepsilon_{equiv}\int_i (E_i)^2\,\mathrm{dv}\,. \qquad (6)$$

Fig. 4 shows the frequency dependence of the computed equivalent electric conductivity and dielectric permittivity in the considered frequency range. The equivalent mass density of the head, necessary for *SAR* estimate, is approximated, by weighted arithmetic mean, with the value 1375 kg/m^3.

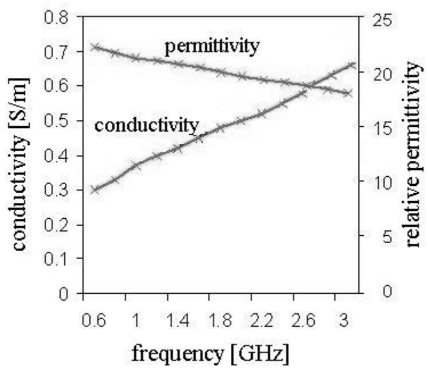


Fig. 4. Equivalent dielectric properties of the homogeneous head

The equivalent properties are useful in the design of experimental mannequins. Tissue equivalent phantoms are used instead of real bodies in the experimental dosimetry. A typical phantom designed for the certification of communication equipment is described in [4] (i.e., the Specific Anthropomorphic Mannequin – SAM) and it consists of a 2 mm polyurethane shell (σ_{shell} = 0.0012 S/m, respectively ε_{shell} = 5), filled with *simulant tissue solution* ($\sigma_{simulant}$ = 0.7 S/m, $\varepsilon_{simulant}$ = 48, at 0.835 GHz and $\sigma_{simulant}$ = 1.7 S/m, $\varepsilon_{simulant}$ = 41, at 1.9 GHz). As one could see, the mentioned values of the *simulant tissue solution* are much higher than the corresponding ones presented in fig. 4 and they are comparable with measured values for brain tissue [11]. However, the presence of the polyurethane shell has a screening effect for the electric field penetration inside the described phantom.

The 3D FEM models used in this wok are based on the same equations (1); the Femlab *3D Electromagnetic Waves* application mode [9] is used; the boundary conditions and the solver options are similar to those specified for the 2D FEM model.

For dosimetric evaluations we propose here, and compare, three 3D FEM models:

- model A – homogeneous head with realistic shape, reconstructed from tomographic slices (shown in fig. 2), filled with *equivalent head* material (fig. 4),
- model B – homogeneous ellipsoidal head, filled with *equivalent head* material (fig. 4),
- model C – homogeneous ellipsoidal head, filled with *simulant brain solution* (properties from [11]).

IV. RESULTS

IV.1 Electric field strength and penetration depth

We computed the E-field strength distribution inside the three head models exposed in the near field of the half wavelength dipole antenna at different frequencies; the antenna is placed at 0.005 m distance from the body surface and the emitted power is set at 1W in all cases in order to express the E-field and *SAR* as rated (per power) values, giving the possibility to better analyze them and to scale them for any other value of the emitted power. Figure 5 shows the distribution of the electric field strength E (maximal time-harmonic values) inside the head model, along an axis with maximal values; the frequency is 1.8 GHz.

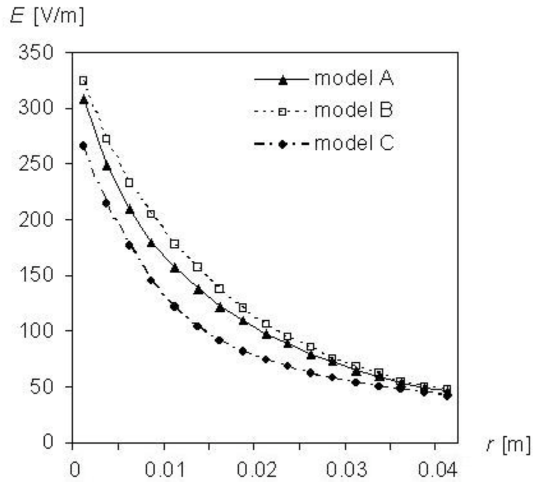


Fig. 5. E distribution (maximal time harmonic values) versus distance r, measured from the surface of the skin, for 3D FEM models (1W, 5mm, 1.8 GHz)

From E-field distributions similar to those displayed in fig. 5 we have computed the penetration depth of the electric field as a function of frequency. The results are given in fig. 6 for the three head models; the antenna emitted power and the distance between antenna and head are the same (1W and 0.005 m).

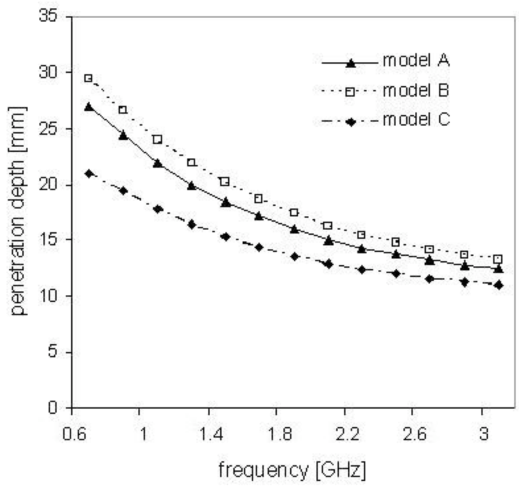


Fig. 6. Penetration depth versus frequency for 3D FEM models (1W, 5mm, 1.8 GHz)

Models A and B behave very similar, which shows that the ellipsoidal shape is a fairly good approximation for the realistic shape of the head. The penetration depth is lower in model C due to the higher conductivity of the simulant brain solution.

IV.2 *SAR* evaluation

SAR distribution inside the head, computed for model A is displayed in the longitudinal and transversal section planes in fig. 7; the same parameters characterise the EMF source.

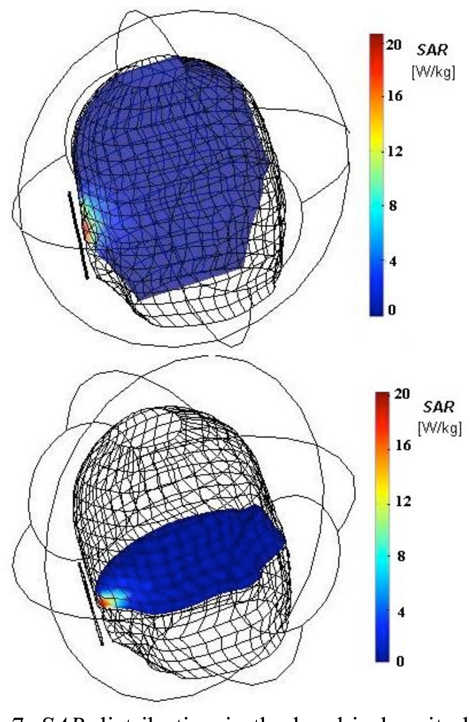


Fig. 7. *SAR* distribution in the head in longitudinal (up) and transversal (down) section planes (1W, 5mm, 1.8 GHz)

We further discuss the significance of the mass-normalized *SAR* over 1g versus 10g of tissue, which represents, for the equivalent biological tissue with the mass density of 1375 kg/m^3, a volume associated to a cube with the edge of 9mm, respectively 19.4mm. The standards suggest that the cube volume should include the maximal local *SAR* values in the exposed area. Because the *SAR*, like the *E*- field in the exposed region is maximal at the surface of the body, the volume is selected with one face on the body surface (in practical cases the curvature could be neglected). Fig. 8 shows, for three significant frequencies (0.9, 1.8 and 2.5 GHz), the following *SAR* computed quantities: the local maximal *SAR* (*SAR*max) and the averaged *SAR* values for 1g and 10g of tissue (*SAR*1g, *SAR*10g). The head is represented with model A and the antenna, placed at 5 mm distance, produces the power of 1W.

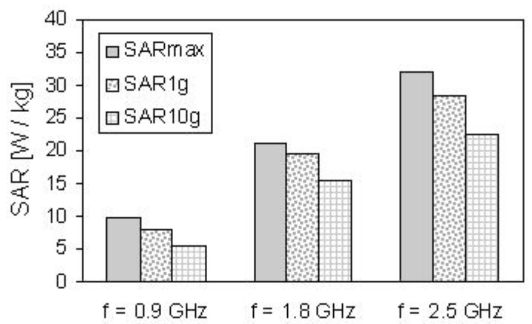


Fig. 8. *SAR* estimates for the type A head models (1W, 5mm)

One could observe that for the same exposure conditions, *SAR*10g is lower than *SAR*1g and *SAR*1g has a value almost comparable to *SAR*max, because *SAR* distribution is highly nonuniform and decreases rapidly with the distance from the peak.

Further we have solved the “inverse problem”, that is the estimate of the admissible power of the radiation source, which produces the SAR1g = 1.6 W/kg, respectively the SAR10g = 2 W/kg, as maximal values permitted by the standards [5, 6]. The results are displayed in fig. 9.

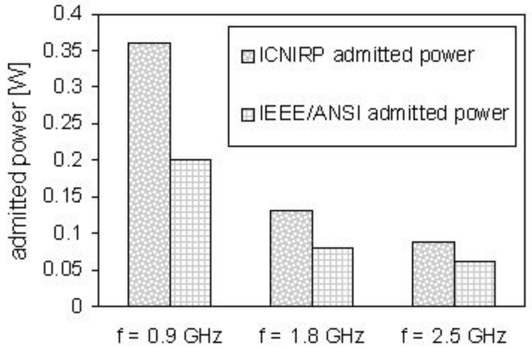


Fig. 9. Admissible emitted power according to ICNIRP guidelines and IEEE/ANSI standard

One could see that the restriction stated by ICNIRP guidelines [5] (adopted also by EC recommendation [8] and by the Australian standard [7]) is more permissive than the one imposed by IEEE/ANSI standard [6].

It is expected that the differences stressed here would be more pronounced in a nonhomogeneous thin layered structure. The skin and fat external layers concentrate the E-field in a narrow region of the head and *SAR*max could have a much more nonuniform distribution than in the homogeneous case [2, 3]. Besides, the averaged value on a volume in the shape of a cube, over tissues with different physical properties seems to have a poor physical significance.

V. CONCLUSIONS

Numerical models are commonly used, as much as experimental phantoms, to evaluate EMF parameters distribution in structures like anatomical tissues when exposed to MW either in day-to-day activities (as mobile phone use) or in medical therapy (hyperthermia, stimulation, etc.). Compared with more sophisticated models, the 2D and 3D FEM models presented in the paper demonstrate advantages in economy of resources, accessibility and rapidity, while the results are sufficiently accurate for global estimates and for comparison with experimental *SAR* and *E* distributions from measurements on phantom human models.

The results presented here are specific for the conditions related to mobile phone use near the head, but the method of equivalence between the heterogeneous anatomical structures and the homogeneous equivalent domains could be also applied to other parts of the body, for the optimal design of simplified 3D numerical models or mannequins for measurements.

The advantages of the numerical modelling compared with experimental measurements are obvious: rapidity in evaluation and versatility of the models - in numerical models the anatomical data could be easily changed. Besides, in experimental studies the required laboratory conditions (anechoic chamber, adequate phantom model and sophisticated instruments) are seldomly accesible.

The work presents the electric field distribution inside 2D and 3D FEM human head models. The penetration depth and the specific energy absorption rate are also computed in a frequency range adequate for microwaves wireless applications. A critical study for the evaluation of *SAR* shows some controversies produced by important differences between the most known and referred human exposure international standards; this situation is quite confusing for manufacturers and for end-users of wireless devices. It is expected that the normalization method for *SAR* limit evaluation will be reconsidered and made more appropriate to the structure of the exposed body; we consider that the characteristic dimension of the integration volume should be made smaller for a more accurate estimate, both in numerical and experimental models. A more localized *SAR* evaluation could be important both for the assessment of thermal and non-thermal biological effects.

Acknowledgment.
The work presented here is part of the research program CEEX code PC-D06-PT10-464 funded by the Romanian Education and Research Department

REFERENCES

[1] C. H. Durney, D. A. Christensen, *Basic Introduction to Bioelectromagnetics,* CRC Press LLC, 2000.

[2] M. Morega, Al. M. Morega, A. Machedon, *Simplified Numerical Models for Microwave Dosimetry in Human Tissue*, Proc. of the 3rd European Medical and Biological Engineering Conference EMBEC'05&IFMBE, Nov. 20-25, 2005, Praga, Czech Rep., ISSN 1727-1983.

[3] A. P. Moneda, M. P. Ioannidou, D. P. Chrissoulidis, *Radio-Wave Exposure of the Human Head: Analytical Study Based on a Versatile Eccentric Spheres Model Including a Brain Core and a Pair of Eyeballs*, IEEE Trans. Biomed. Eng., Vol. 50, 2003, p.667- 676.

[4] CTIA, *Certification Program Test Plan for Mobile Station Over the Air Performance Cellular Telecommunications & Internet Association Method of Measurement for Radiated RF Power and Receiver Performance*, Revision 2.0, March 2003.

[5] ICNIRP, *Guidelines for Limiting Exposure to Time-varying Electric, Magnetic and Electromagnetic Fields (up to 300 GHz)*, Health Phys., 74, No. 4, 1998, p.494–522

[6] ANSI/IEEE, *Safety Levels with respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz*, IEEE Standard C95.1-1999

[7] Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), *Maximum Exposure Levels to Radiofrequency Fields - 3 kHz to 300 GHz*, Radiation Protection Series Publication no. 3, 2002

[8] Council of the European Union, *Council Recommendation of 12 July 1999 on the Limitation of Exposure of the General Public to Electromagnetic Fields (0 Hz to 300 GHz)*, Official Journal of the European Communities L199/519/EC, 59-70, 1999

[9] COMSOL AB., FEMLAB v. 2.3 (2002), v. 3 (2004), *Users Guide, Electromagnetics Module*, Stockholm, Sweden

[10] MIT Artificial Intelligence Laboratory, 3D Slicer v. 1.3.0. (2002), *Open Source development project*, USA

[11] C. Gabriel, S. Gabriel, *Dielectric Properties of Body Tissues at RF and Microwave Frequencies*, Report for Armstrong Laboratory (AFMC), Occupational and Environmental Health Directorate - RF Radiation Division, USA, 2002